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# Tribological and Mechanical Comparison of Sintered and Hipped PM212: High Temperature Self- Lubricating Composites

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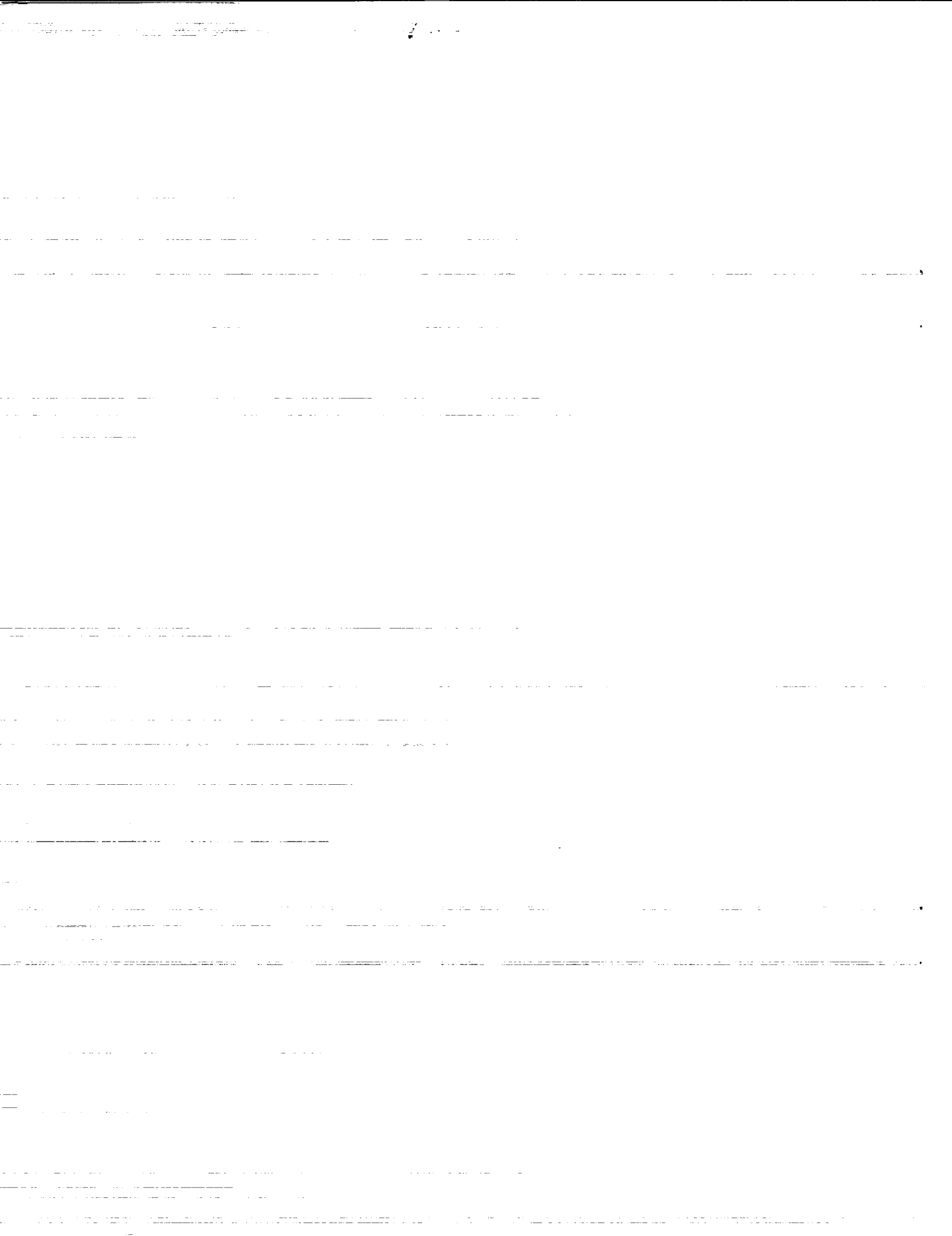


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PM212: HIGH TEMPERATURE SELF-LUBRICATING  
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TRIBOLOGICAL AND MECHANICAL COMPARISON OF SINTERED AND HIPPED  
PM212: HIGH TEMPERATURE SELF-LUBRICATING COMPOSITES

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SUMMARY

Selected tribological, mechanical and thermophysical properties of two versions of PM212 (sintered and hot isostatically pressed, HIPped) are compared. PM212, a high temperature self-lubricating composite, contains 70 wt % metal bonded chromium carbide, 15 wt %  $\text{CaF}_2/\text{BaF}_2$  eutectic and 15 wt % silver. PM212, in the sintered form is about 80 percent dense and has previously been shown to have good tribological properties from room temperature to 850 °C. This paper reports tribological results of a fully densified, HIPped version of PM212 and compares them to sintered PM212. In addition, selected mechanical and thermophysical properties of both types of PM212 are discussed and related to the tribological similarities and differences between the two PM212 composites.

In general, both composites display similar friction and wear properties. However, the fully dense PM212 HIPped composite exhibits slightly lower friction and wear than sintered PM212. This may be attributed to its generally higher strength properties. The sintered version displays stable wear properties over a wide load range indicating its promise for use in a variety of applications. Based upon their properties, both the sintered and HIPped PM212 have potential as bearing and seal materials for advanced high temperature applications.

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## INTRODUCTION

Recent research at NASA, Lewis Research Center has led to the development of a class of self-lubricating high temperature composite materials known as PM212.<sup>1</sup> PM212 is comprised of a matrix of metal bonded chromium carbide with silver and fluoride additions which act as low and high temperature lubricants, respectively. PM212 is a further development of the PS212 plasma-spray coating which has been shown to provide low friction and wear over a wide temperature range in a variety of environments including air, hydrogen and helium.<sup>2-4</sup>

The development of a powder metallurgy form of PS212, designated PM212 was driven by the need to expand the potential applications for this unique self-lubricating composite system. For example, PS212 was successfully applied as a cylinder wall coating to lubricate the piston rings in a Stirling engine which used hydrogen at 760 °C as its working gas.<sup>5</sup> The coating has also performed well as backup lubrication for foil bearings operating from 25 to 650 °C.<sup>6</sup> However, there are potential applications which do not lend themselves to coating application. Some examples are valve guides for low heat rejection engines and variable stator vane bushings for turbines. In these instances, it is impractical if not impossible to successfully coat these parts by plasma spraying. Thus manufacturing composite parts by powder metallurgy techniques is a next logical approach.

The powder metallurgy form of the composite system, PM212, was first demonstrated as pins made by cold isostatic pressing followed by sintering in hydrogen. These pins were slid against superalloy test disks over a wide temperature spectrum.<sup>1</sup> This production route yielded parts which were about 80 percent dense and displayed good tribological properties.

Subsequently, full density processing by a Cold Isostatic Pressing (CIP) then Hot Isostatic Pressing (HIP) processing route has produced parts which have superior strength properties but as yet unreported tribological properties.<sup>7</sup> This paper reports the tribological properties of the fully densified HIPped PM212 and compares them to the 80 percent dense sintered product. In

addition, the thermophysical and mechanical properties of both forms are highlighted and discussed. It is hoped that this information will aid in the timely use of PM212 for advanced high temperature tribological applications.

### Materials

PM212 is a composite made from three components; 70 wt % metal bonded chromium carbide, 15 wt %  $\text{BaF}_2/\text{CaF}_2$  eutectic and 15 wt % silver. The metal bonded chromium carbide forms a wear resistant matrix and the fluorides and silver act as high and low temperature lubricants, respectively. The rationale for this material selection has been described in detail in the literature.<sup>8</sup> The three components are combined as blended powders. The exact composition and particle sizes used are listed in Table 1.

For tribological evaluation, PM212 pins are slid against René 41, nickel based superalloy disks using a pin-on-disk tribometer. The disks are precipitation hardened to 34 on the Rockwell C scale. The disk composition and representative properties are given in Table 2.

## APPARATUS AND PROCEDURES

### PM212 Processing

The PM212 pin specimens were produced by one of two processing routes; either cold compaction then cold isostatic pressing followed by sintering or cold compaction then cold isostatic pressing followed by hot isostatic pressing. These techniques are illustrated in Fig. 1 and described elsewhere in detail.<sup>9-11</sup> They will, therefore, only briefly be described here.

The cold compaction of the powder is carried out in a steel die at a pressure of 54.2 MPa to produce cylindrical slugs. Following cold compaction, the slugs are cold isostatically pressed (CIPped) in a rubber mold at 406 MPa. For sintered specimens the CIPped slugs are placed in a hydrogen furnace and sintered at 1100 °C for 20 min. The heating and cooling rates are constant at 10 °C/min. For the HIPped specimens, the CIPped slugs are vacuum sealed in a stainless steel can lined with graphite foil which prevents interfacial chemical reactions between

the PM212 slug and the stainless steel can. HIPping is done in pressurized argon (138 MPa) at 1100 °C for 20 min. The heating and cooling rates are 6 and 12 °C/min respectively and the pressurization and depressurization rates are 0.75 and 1.5 MPa/min respectively. The PM212 specimens prepared by sintering are approximately 80 percent dense and the HIPped PM212 specimens are essentially 100 percent dense. Figures 2 and 3 show representative microstructures of sintered and HIPped PM212.

### Tribological Evaluation

Tribopin Machining: The resulting PM212 slugs are finish machined into test pins by diamond grinding. Clean water was used as the grinding coolant to prevent contamination by conventional grinding oils. The machined pin specimens were 9.5 mm in diameter, 15 mm long and were radiused at each end with a 4.76 mm radius of curvature. With proper steps taken to account for shrinkage and using standard near net shape processing techniques, specimens could probably be prepared close to the desired dimensions. No such steps were taken at this time.

Tribotesting Procedures: The tribological properties of sintered and HIPped PM212 pins were evaluated by sliding them against René 41 nickel based superalloy disks in a pin on disk tribometer at temperatures from 25 to 850 °C. The test atmosphere was air with a relative humidity of 35 percent at 25 °C and the sliding velocity was 2.7 m/s. For most of the tests the applied load was 4.9 N. However, some tests with sintered PM212 were conducted at loads up to 19.6 N at 760 °C to ascertain the effect of load on friction and wear at a typical use temperature.

Figure 4 shows the pin on disk tribometer used to evaluate the specimens. With this configuration, a hemispherically tipped pin (9.5 mm diameter 15 mm long) is slid against the face of a superalloy disk. The pin generates a 51-mm diameter wear track on the disk, and, as the pin wears, a flat circular wear scar forms on the pin. The disk is heated with a low frequency induction heater and temperature was measured with an infrared pyrometer capable of

measuring surface temperatures from 100 to 1400 °C with about  $\pm 5$  percent accuracy. Tests were run for 30 min after which the specimens were removed to make wear measurements. At least two tests at each temperature were performed and a minimum of two specimen sets were tested. For the load effect tests of sintered PM212, the test interval varied from 10 to 30 min to make more frequent wear measurements.

### Mechanical Property Evaluation

Specimens: To evaluate the mechanical and thermophysical properties of PM212 specimens were prepared from the consolidated slugs by wire Electrode Discharge Machining (EDM) using clean water as the machining fluid. Compressive test specimens were cylindrical with lengths of 10 mm and diameters of 5 mm. For tensile strength measurements, button head specimens with a gage length of 32 mm and diameter of 3 mm were used. Table 3 gives details on test specimen geometries and techniques used to measure the mechanical properties (compressive strength, tensile strength, elastic modulus) and thermophysical properties (thermal expansion coefficient, specific heat, thermal diffusivity).

Mechanical Evaluation: The details of the mechanical and thermophysical property evaluation of PM212 as well as the metal bonded carbide matrix are described in Refs. 7 and 12 and will not be repeated here. Selected results are presented here in order to relate them to the comparison of the tribological behavior of the sintered and HIPped PM212 and to enhance the availability of design information.

## RESULTS AND DISCUSSION

### Tribological Properties

The friction and wear properties for the sintered and HIPped PM212 are given in Table 4 and the friction behavior is plotted in Fig. 5. The friction coefficient is defined as the ratio of the friction force to the applied load and the wear factor is defined as the wear volume divided by both the load and the sliding distance. Under the test conditions studied here, the sintered

form of PM212 performed similarly to the HIPped form. Friction for the HIPped version was slightly lower but the differences are within data scatter for this material. Wear factors for the HIPped PM212 are lower than for the sintered PM212 except at 850 °C where the sintered version experiences less wear. The reason for this effect is not clear but may be related to the significant compressive strength reduction of the composite above 750 °C.

For sintered PM212, at loads from 4.9 to 19.6 N, both the wear rate and the friction force are a linear function of load giving a constant friction coefficient and wear factor (Fig. 6). The relationships follow classical tribology theories for solid lubrication within the same wear regime. These results indicate that, for these test conditions, the load capacity for the sintered PM212 is not exceeded. If the load capacity had been exceeded, there would have been a sharp, discontinuous increase in the wear rate. The typical wear scar diameter on the pin was about 2 mm giving nominal contact stresses during the tests of approximately 1.5 to 6 MPa for loads of 4.9 to 19.6 N respectively. Load limitations of the apparatus precluded testing at higher loads to determine a load capacity. These tests are planned for equipment with higher loading capabilities.

#### Mechanical and Thermophysical Properties

The following results are from a detailed properties study reported in Refs. 7 and 12. The properties determined are highlighted here to help foster an understanding of the similarities and differences between the two forms of PM212 and also to provide comprehensive information needed for the successful engineering application of PM212.

#### Compressive Behavior

The compressive strength data for sintered PM212 and HIPped PM212 are given in Table 5 and plotted in Fig. 7. From the data it can be seen that, under compression, the fully dense HIPped PM212 is about three times stronger than the sintered version over the entire test temperature range from 25 to 900 °C. At 25 and 350 °C both forms of PM212 display brittle



behavior with only a slight decrease in strength from 25 to 350 °C. A significant decrease in strength occurs at 760 and 900 °C as well as an increase in ductility.

#### Tensile Behavior

The tensile strength data for PM212 is shown in Table 6. Again, the HIPped PM212 is substantially stronger than the sintered PM212; about 2.5 times at room temperature and 3.5 times as strong at 760 °C. In tension, none of the specimens displayed measurable ductility except the HIPped specimens at 760 °C. The tensile strength of PM212 is relatively low compared to other high temperature materials such as superalloys. However, since many bearing and seal material applications experience predominantly compressive loading, tensile strength is not always a major engineering factor.

#### Young's Modulus

The Young's elastic modulus was measured using an acoustic technique in which the propagation speed of sound waves through a specimen is used to calculate its elastic modulus.<sup>7</sup> The modulus for the sintered PM212 is about 95 GPa at room temperature. The modulus for the HIPped PM212 is about twice that value, 175 GPa. These results further indicate that the strength and stiffness of PM212 is enhanced by full density processing.

#### Thermal Expansion Coefficient

The linear coefficient of thermal expansion was measured with a dilatometer from 25 to 850 °C and the results are given in Table 7 and plotted in Fig. 8. Both forms of PM212, sintered and HIPped, showed approximately the same expansion behavior. From 25 to about 550 °C, the thermal expansion coefficient was approximately  $12.5 \times 10^{-6}/^{\circ}\text{C}$ . From 550 to 850 °C, the coefficient was higher, 16.1 and  $16.7 \times 10^{-6}/^{\circ}\text{C}$  for the sintered and the HIPped PM212, respectively.

The thermal expansion coefficient for the PM212 is about the same as the metal bonded carbide matrix at temperatures below 550 °C. Above 550 °C, the expansion coefficient is

probably affected by the fluoride eutectic which has a much higher expansion coefficient ( $\approx 22.0 \times 10^{-6}/^{\circ}\text{C}$ ) than the carbide matrix ( $\approx 13.0 \times 10^{-6}/^{\circ}\text{C}$ ).<sup>7,12</sup> The composite nature of PM212 and the widely differing expansion coefficients of the constituents is the most likely reason for the change in expansion coefficient around 550 °C.

#### Specific Heat, Thermal Diffusivity: Calculated Thermal Conductivity

The thermal conductivity was calculated from measured values of density, specific heat and thermal diffusivity. The results are given in Table 8 and plotted in Fig. 9. From the figure, it is clear that the fully densified HIPped PM212 has much higher thermal conductivity than the sintered PM212. For both forms of PM212 the thermal conductivity increases with temperature.

Thermal conductivity in multiphase systems is often dominated by the properties continuous phases. In the case of PM212, the continuous phases are the carbide matrix and the fluorides. These materials have relatively low thermal conductivities, therefore, the thermal conductivity of PM212 is also relatively low especially when compared to good thermal conductors like copper and aluminum. Table 9 lists the thermal conductivity of PM212 along with a variety of other engineering materials. Although the thermal conductivity of PM212 is low compared to copper, it compares favorably to many engineering materials such as austenitic stainless steel and some high conductivity ceramics like silicon carbide.

#### COMPARISON OF TRIBOLOGICAL AND ENGINEERING PROPERTIES

The tribological results indicate that both the sintered and HIPped forms of PM212 exhibit good friction and wear properties over a wide temperature range. The fully dense HIPped PM212 showed lower average wear and about the same friction as sintered PM212. The similarities in friction behavior can probably be attributed to the fact that both composites have the same composition. In other words, under these test conditions the tribological properties are probably dominated by lubricating transfer films of silver and fluorides,<sup>2</sup> not mechanical properties.

Sliding wear tests of sintered PM212 at loads from 4.9 to 19.6 N resulted in linearly increased wear indicating that the load capacity limit for PM212 was not exceeded (Fig. 6). This is not surprising when it is considered that the contact stress encountered during the tribotest was only about 5 to 10 MPa compared to a compressive strength of sintered PM212 of at least 100 MPa.

Tribotests at higher loads are necessary to ascertain the tribological load capacity for PM212 above which the wear mechanism changes, with wear increasing substantially more than in a simple linear fashion. From these tests it can be concluded that PM212, even in sintered form, can be used under a wide variety of loading conditions. At much higher loads and contact stresses, the HIPped PM212 may provide substantially better wear resistance than the sintered PM212 based upon its superior mechanical strength properties.

In general, HIPped PM212 is approximately three times stronger than sintered PM212. The differences in properties can be attributed mostly to the presence of porosity in the sintered PM212. The porosity lowers the strength and affects some of the thermophysical properties such as conductivity. In order to put the strength properties of PM212 into perspective, it is instructive to compare the strength properties of PM212 to other more conventional bearing materials which are only suited to low temperature applications.

Figure 10 shows the compressive strength of PM212 compared to conventional graphite and bearing bronzes. From the figure, it is clear that at room temperature, PM212 is much stronger than other bearing materials and is approximately as strong even at very high temperatures which conventional bearing materials cannot withstand and are not tribologically useful. Figure 10 also shows the maximum use temperature for PM212 and competing bearing materials. The combination of adequate mechanical, tribological and thermophysical properties along with unique temperature capabilities make the PM212 materials viable candidates for a wide variety of high temperature bearing and seal applications.

## RESULTS SUMMARY

1. Both the sintered and the HIPped PM212 display about the same friction behavior over the entire temperature range tested. This similarity is probably due to the fact that, under these test conditions, the composites' composition, which is the same for both forms of PM212, dominates the friction behavior.
2. The fully densified HIPped PM212 exhibits better overall wear properties which may be related to the fact that it is about three times stronger than the 80 percent dense sintered PM212.
3. Both the sintered and HIPped PM212, which contain about 35 wt % chromium carbide, exhibit little ductility and are much stronger in compression than in tension. This behavior is characteristic of ceramic and ceramic based materials.
4. The strength properties of PM212 are relatively constant up to 350 °C and are significantly reduced at higher temperatures. At 760 and 900 °C the HIPped PM212 retains more strength than the sintered PM212 making it a preferable material choice for high temperature higher stress applications.

## CONCLUDING REMARKS

PM212 displays thermophysical properties, such as thermal conductivity and expansion, that are similar to some stainless steels and ceramics such as silicon carbide. This makes it an attractive material choice (to minimize thermal expansion mismatch and hot spots) for applications which include these and other high temperature engineering materials.

Based upon the results presented here, it is apparent that both the sintered and HIPped PM212 have adequate compressive strength and acceptable thermophysical properties which make them potential candidates for sliding bearing and seal applications at temperatures to 760 °C. The HIPped version, which is stronger, may be useful in lightly loaded applications to 900 °C.

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TABLE 1. - COMPONENTS OF PM212

Component	Composition, wt %	Composition, vol %	Particle size U.S. sieve no., ( $\mu\text{m}$ )
Bonded chromium carbide: 70 wt % of PM212			
$\text{Cr}_3\text{C}_2$	45	47	-200 + 400 (74 to 35)
Ni	28	22	
Co	12	10	
Cr	9	9	
Mo	2	1	
Al	2	5	
B	1	3	
Si	1	3	
Silver metal: 15 wt % of PM212			
Ag	100	100	-100 + 325 (150 to 44)
Prefused eutectic: 15 wt % of PM212			
$\text{BaF}_2$	62	52	-200 + 325 (74 to 44)
$\text{CaF}_2$	38	48	

**TABLE 2. - MECHANICAL PROPERTIES AND COMPOSITION  
OF RENÉ 41 DISK MATERIAL<sup>a</sup>**

Material .....	R41
Elemental weight percent	
Ni .....	Balance
Cr .....	19
Co .....	11
Mo .....	10
Ti .....	3.1
Al .....	1.5
Fe .....	0.3
Ultimate tensile strength, MPa	
25 °C .....	1400
650 °C .....	1314
Yield strength 0.2 percent offset, MPa	
25 °C .....	1043
650 °C .....	982
Hardness at 25 °C .....	RC 38 to 40

<sup>a</sup>Typical manufacturer's data handbook values.



TABLE 3. - TEST TECHNIQUES AND SPECIMEN GEOMETRIES USED TO EVALUATE PM212

Test	Technique	Specimen geometry	Specimen dimensions, mm
Tribological evaluation	Pin-on-disk	Hemispherically tipped pin	9.5 dia. $\times$ 15 length
Compressive strength	Constant strain rate compression	Cylindrical rod	5 dia. $\times$ 10 length
Tensile strength	Constant strain rate tension	Button head rod	3 dia. $\times$ 32 gage length
Elastic (Young's) modulus	Ultrasonic pulse echo method	Square wafer	25 square $\times$ 2.5 thick
Thermal expansion	Dilatometry	Long cylindrical rod	12 dia. $\times$ 50 length
Thermal diffusivity, $\alpha$	Laser flash method	Cylindrical wafer	12.5 dia. $\times$ 3.8 thick
Specific heat, $C_p$	Differential scanning calorimetry	Cylindrical wafer	5.6 dia. $\times$ 1.65 thick
Thermal conductivity	Calculated from $C_p$ , $\alpha$ , and density	-----	-----

TABLE 4. - TRIBOLOGICAL DATA SUMMARY FOR SINTERED AND HIPped PM212<sup>a</sup>

Temperature, °C	$\mu$		K pin, mm <sup>3</sup> /N-m		K disk, mm <sup>3</sup> /N-m	
	Sinter	HIP	Sinter	HIP	Sinter	HIP
25	0.35±.05	0.37±.04	3.2±1.5×10 <sup>-5</sup>	1.8±.4×10 <sup>-5</sup>	7.0±2.0×10 <sup>-5</sup>	0.45±.11×10 <sup>-5</sup>
350	.38±.02	.32±.07	3.9±1.8×10 <sup>-5</sup>	2.5±.3×10 <sup>-5</sup>	3.5±1.0×10 <sup>-6</sup>	.85±.4×10 <sup>-5</sup>
760	.35±.06	.31±.04	3.6±.9×10 <sup>-6</sup>	.07±.04×10 <sup>-5</sup>	1.0±.6×10 <sup>-5</sup>	2.2±.8×10 <sup>-5</sup>
850	.29±.03	.29±.04	4.1±2.0×10 <sup>-6</sup>	.83±.10×10 <sup>-5</sup>	5.0±1.0×10 <sup>-6</sup>	≈0, Transfer
Averages	0.34	0.32	2.0×10 <sup>-5</sup>	1.3×10 <sup>-5</sup>	2.2×10 <sup>-5</sup>	0.88±×10 <sup>-5</sup>

<sup>a</sup>Uncertainties represent one standard deviation of the mean for the friction coefficients and the data scatter band for the wear data.

TABLE 5. - COMPRESSIVE STRENGTH DATA FOR PM212

 $2.1 \times 10^{-4} \text{ s}^{-1}$  STANDARD STRAIN RATE<sup>a</sup>

Property	Temperature, °C	Sintered PM212	HIPped PM212
Proportional limit, MPa	25	324±7	807±26
	350	320±12	730±64
	760	77±6	304±24
	900	13±7	34±15
0.2 percent yield stress, MPa	25	346±3	937±21
	350	334±13	840±16
	760	95±4	318±29
	900	20±8	67±25
Maximum stress, MPa	25	346±3	967±23
	350	334±13	851±19
	760	109±4	321±31
	900	35±2	107±38
Plastic strain at maximum stress	25	0.002±0.003	0.004±0.0007
	350	.002±0	.003±.0003
	760	.010±0	.003±.0013
	900	.027±.009	.018±.0034

<sup>a</sup>Uncertainties represent one standard deviation.

TABLE 6. - TENSILE TEST DATA FOR PM212

Test temperature, °C	Failure strength, MPa		Elongation, percent	
	Sintered PM212	HIPped PM212	Sintered PM212	HIPped PM212
25	45	118	0.0	0.0
550	46	118	0.0	0.0
760	25	84	0.0	0.1

TABLE 7. - LINEAR COEFFICIENT OF  
THERMAL EXPANSION OF PM212 AND  
COMPONENTS

[Test conditions: nitrogen atmosphere.]

Material	Coefficient of thermal expansion, $^{\circ}\text{C}^{-1}$	Temperature range, $^{\circ}\text{C}$
HIPped	$12.2 \times 10^{-6}$	25 to 550
PM212	18.7	550 to 850
	14.4	25 to 850
Sintered	12.7	25 to 500
	17.2	550 to 850
PM212	13.8	25 to 850
Metal bonded carbide	12.2	25 to 550
	14.3	550 to 850
	13.3	25 to 850
Ag	28.4	<sup>a</sup> 25 to 900
CaF <sub>2</sub>	36.6	<sup>a</sup> 25 to 627
BaF <sub>2</sub>	25.8	<sup>a</sup> 25 to 577
Cr <sub>3</sub> C <sub>2</sub>	12.1	<sup>a</sup> 25 to 927
Ni	18.3	<sup>a</sup> 25 to 927

<sup>a</sup>Thermophysical Properties of Matter,  
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et al. IFI/Plenum, NY, 1975.

TABLE 8. - THERMAL CONDUCTIVITY CALCULATIONS

Sample	Temperature, °C	Density, gm, cm <sup>-3</sup>	Specific heat, W, s, gm <sup>-1</sup> , K <sup>-1</sup>	Diffusivity, cm <sup>2</sup> , sec <sup>-1</sup>	Conductivity, W, cm <sup>-1</sup> , K <sup>-1</sup>
Sintered PM212	23.0	5.141	0.4780	0.04050	0.09952
	100.0	↓	.5150	.04030	.10670
	200.0	↓	.5410	.04070	.11320
	300.0	↓	.5570	.04140	.11855
	400.0	↓	.5750	.04300	.12711
	500.0	↓	.6020	.04350	.13460
	600.0	↓	.6280	.04560	.14722
	700.0	↓	.6570	.04670	.15774
	800.0	↓	.6950	.04670	.16686
	900.0	↓	.7480	.04430	.17035
HIPped PM212	23.0	6.566	0.4870	0.04240	0.13558
	100.0	↓	.5270	.04240	.14672
	200.0	↓	.5570	.04310	.15763
	300.0	↓	.5730	.04470	.16818
	400.0	↓	.5870	.04670	.17999
	500.0	↓	.6130	.04830	.19441
	600.0	↓	.6490	.04930	.21008
	700.0	↓	.6820	.05050	.22614
	800.0	↓	.7190	.05120	.24171
	900.0	↓	.7600	.04860	.24252

TABLE 9. - THERMAL CONDUCTIVITY

Materials	Thermal conductivity, $\text{Wcm}^{-1}\text{k}^{-1}$	
	25 °C	927 °C
Diamond	9.0	-----
Ag	4.3	3.6
Cu	4.0	3.4
Au	3.2	2.6
Al	2.4	-----
SiC	.3 to 2.0	.14 to .6
Carbon/graphite	1.3	.55
Gray cast iron	.80	-----
Bearing bronze	.80	-----
304SS	.16	<sup>a</sup> .21 (500 °C)
PM212 (HIPped)	.13	.24
Ni-Cr superalloy	.11 to .12	<sup>a</sup> .24 to .27
PM212 (Sintered)	.10	.17
$\text{Si}_3\text{N}_4$	.05	.07
$\text{ZrO}_2$	.018	.02

From: Thermophysical Properties of Matter,  
Vols. 1 and 2. Thermal Conductivity,  
Touloukian, Y.S., Powell, R.W., Ho, C.Y.,  
and Kleinens, P.G., IFI/Plenum, NY, 1970.

Except: <sup>a</sup>Manufacturing data.

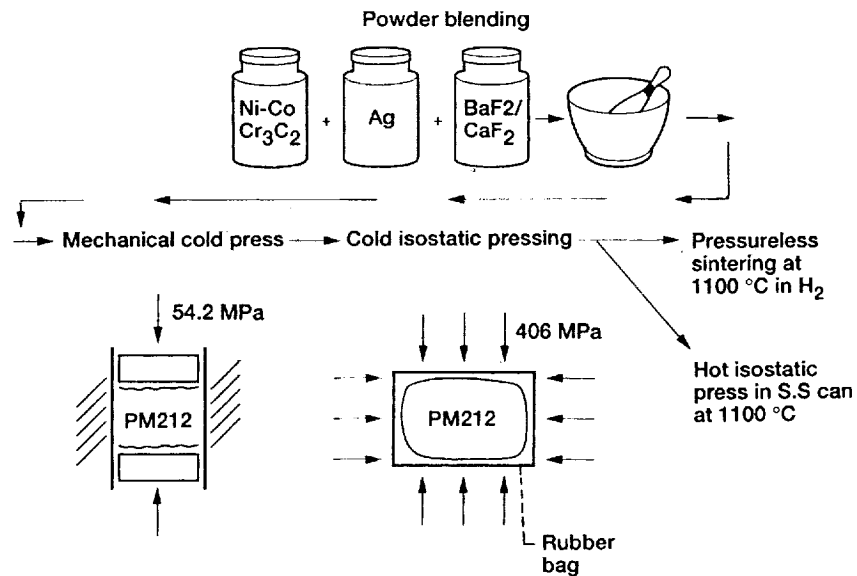
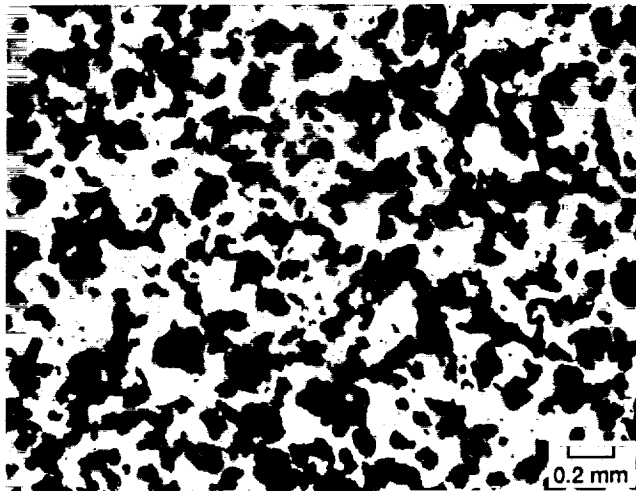
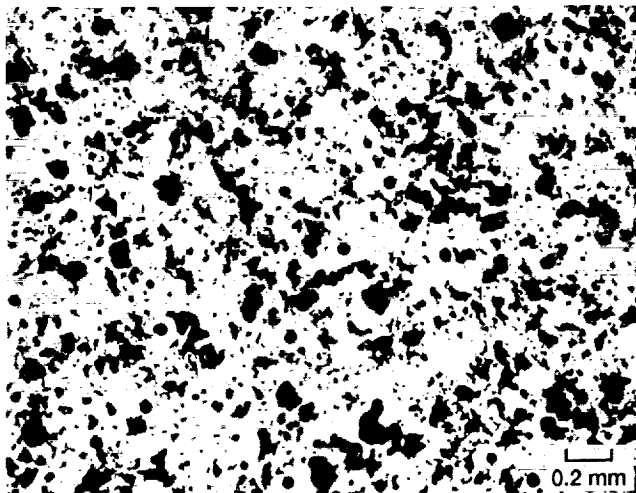


Figure 1. —Powder metallurgy (PM) processing route to make PM212 components.

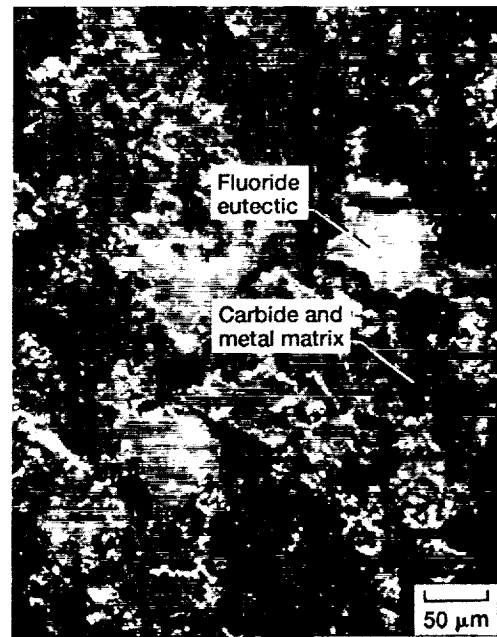


(a) PM212-Sintered.

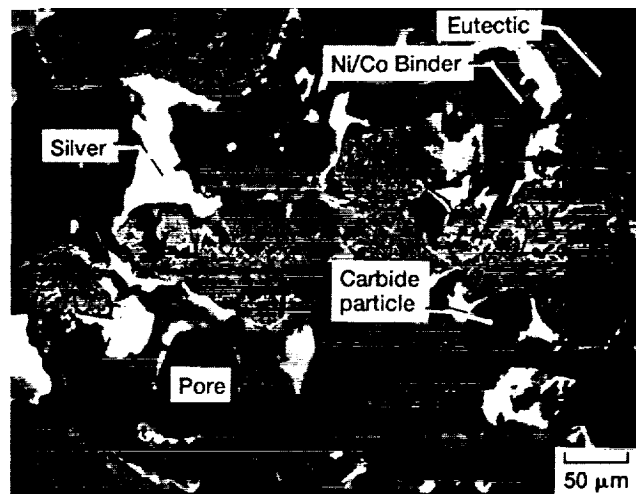


(b) PM212-HIPped.

Figure 2.—Illustration of density difference between 80% dense sintered PM212 (Fig 2a) and 100% dense HIPped PM212 (Fig 2b).



(a) Optical (oblique) illumination.



(b) Backscattered electron micrograph.

Figure 3.—Compositional photomicrographs of sintered PM212 showing microstructure under oblique optical illumination (a) and backscattered electron imaging (b).



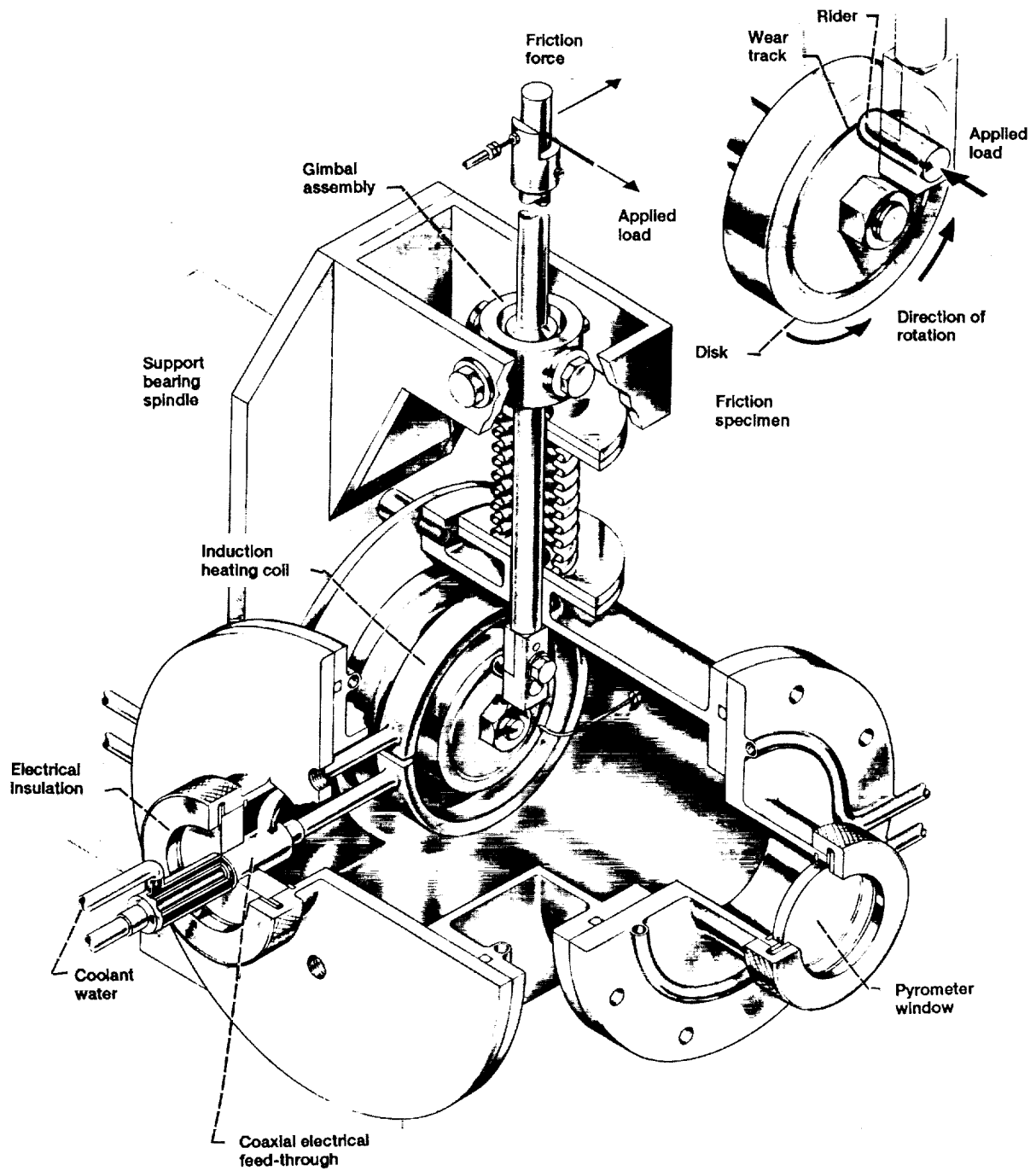


Figure 4. —High-temperature friction apparatus used to slide PM212 pins against superalloy disk.

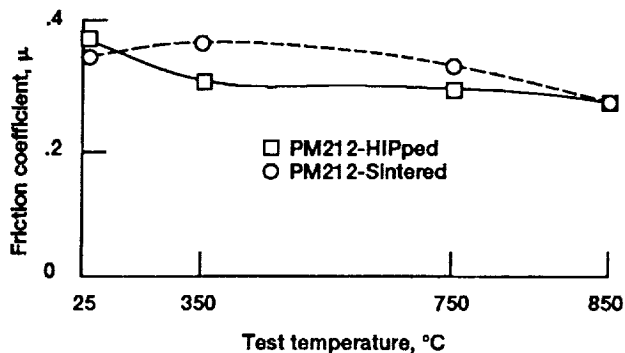


Figure 5.—Friction coefficient versus temperature for both sintered and HIPped PM212. Test conditions: 4.9 N load, 2.7 m/s sliding velocity, air at 35% R.H. at 25 °C.

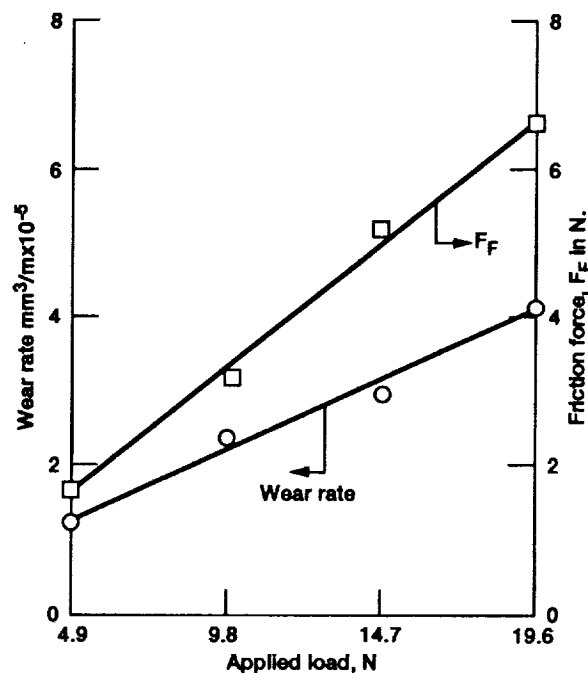


Figure 6.—Friction force and wear rate as a function of applied load for sintered PM212. Linear relationship follows classic tribological models. For average 2mm diameter wear scar, 4.9 N load is roughly equivalent to 1.5 MPa contact stress.

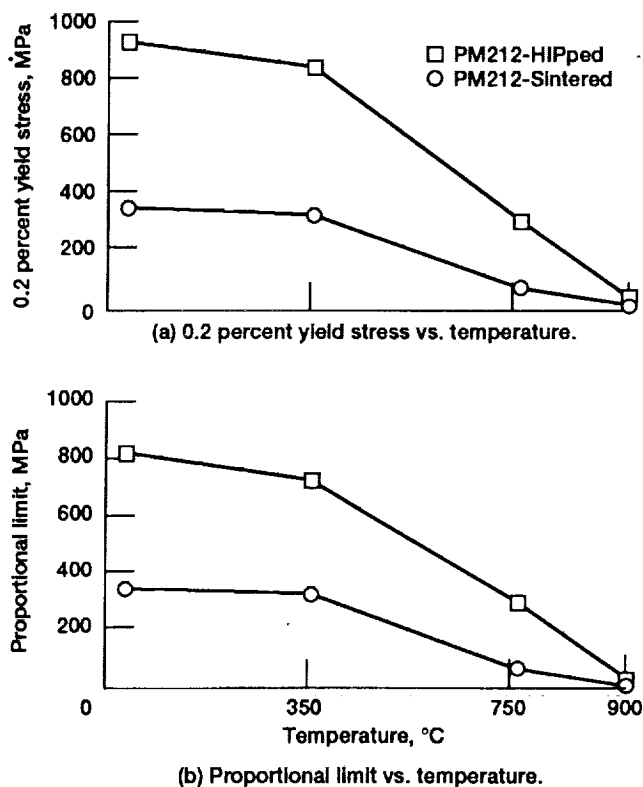


Figure 7.—Compressive strength properties of sintered and HIPped PM212.

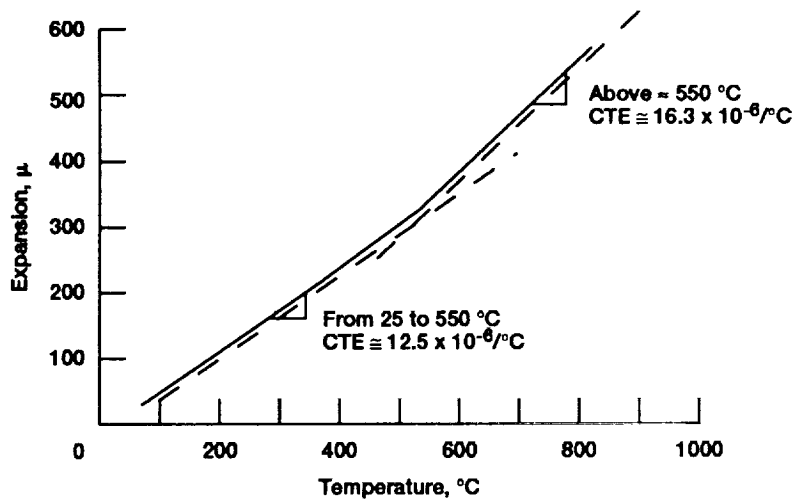


Figure 8.—Thermal expansion versus temperature for both sintered and HIPped PM212. Specimen length (gage length) 50 mm. Note that the thermal expansion coefficient (slope) increases at about 550 °C

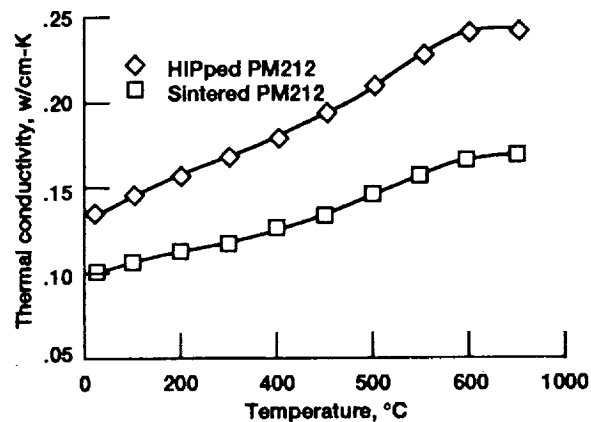
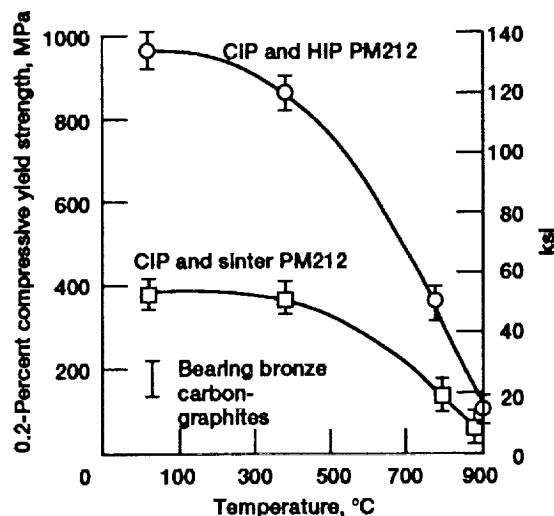
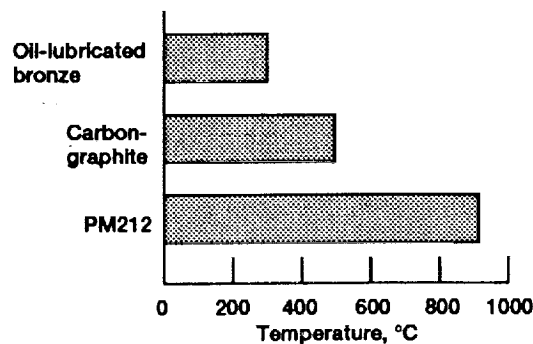


Figure 9.—Thermal conductivity versus temperature: for both sintered and HIPped PM212.



a) Compressive strength comparison of self lubricating bearing materials.



b) Maximum use temperature for PM212 far exceeds conventional bearing materials

Figure 10.—Compressive strength and maximum use temperature comparison of PM212 and conventional bearing materials.

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13. ABSTRACT (Maximum 200 words)  Selected tribological, mechanical and thermophysical properties of two versions of PM212 (sintered and hot isostatically pressed, HIPped) are compared. PM212, a high temperature self-lubricating composite, contains 70 wt % metal bonded chromium carbide, 15 wt % $\text{CaF}_2/\text{BaF}_2$ eutectic and 15 wt % silver. PM212 in the sintered form is about 80 percent dense and has previously been shown to have good tribological properties from room temperature to 850 °C. This paper reports tribological results of a fully densified, HIPped version of PM212 and compares them to sintered PM212. In addition, selected mechanical and thermophysical properties of both types of PM212 are discussed and related to the tribological similarities and differences between the two PM212 composites. In general, both composites display similar friction and wear properties. However, the fully dense PM212 HIPped composite exhibits slightly lower friction and wear than sintered PM212. This may be attributed to its generally higher strength properties. The sintered version displays stable wear properties over a wide load range indicating its promise for use in a variety of applications. Based upon their properties, both the sintered and HIPped PM212 have potential as bearing and seal materials for advanced high temperature applications.				
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